

# Power Electronics Intelligence at the Grid Edge - Enables Energy Budgeting

Jorge A. Ramos-Ruiz, Prasad Enjeti, Le Xie  
Department of Electrical & Computer Engineering  
Texas A&M University  
College Station, TX, USA  
email: enjeti@tamu.edu

**Abstract.** In this paper, a self-organizing power electronic converter with control intelligence at the edge of the electric distribution network is proposed. The proposed framework, termed Power Electronics Intelligence at the Network Edge (PINE), has the potential to make the future electricity delivery system more internet-like (i.e. intelligence at the network edge). This approach addresses the need to mobilize distributed energy resources, as well as to endow the power grid with edge-based intelligence to provide local communities with at least the critical portion of their electricity needs, hence improving the overall resiliency of the electric grid. The proposed concept has many advantages including: a) energy budgeting is possible and can be enabled remotely, b) power flow is bidirectional, c) output voltage is regulated via PWM control, d) distribution voltage can vary over a wider range, e) input current is harmonic free at unity power factor. Simulation and hardware results validate the proposed concept.

**Keywords**—Energy budgeting, resilience, volt var control.

## I. INTRODUCTION

The topic of electric distribution system optimization and restoration has attracted increased attention thanks to the smart grid investments across the world. Examples of distribution system optimization and Volt-Var regulation efforts are shown in [1,2]. Further, [3,4] explore the possibility of using microgrids as a way to improve power supply resilience during natural disasters. This is done by adding diversity to the energy source, reducing the dependency on certain essential infrastructures to operate a system (or lifelines). Theoretical calculations confirmed via Monte Carlo simulations are employed to show the higher availability in the presence of renewable energy sources. They do not however, show disaster reconfiguration architecture and energy budgeting aspects that are essential under post-disaster scenarios.

Assessments post-2005 bombings in London conclude that cell phone networks are not resilient, however, the Internet designed as a network with its intelligence at the edge is highly resilient [5]. Such resiliency is needed for power distribution too since electricity is the very lifeblood of modern civil society, just as much as communication is. There is urgent need to restore the critical needs, if not all the needs, of access to electricity.

Traditionally, residential rooftop solar PV/Battery systems are installed employing dedicated converters for each the solar panel and the battery [6]. The main advantages are: a) energy cost reduction, b) peak shaving, c) volt var control, d) consumption in rural areas. Fig. 1 shows such a system where in the roof-top PV and the battery energy storage system (BESS) employ separate dc-ac converters interfaced to the grid.

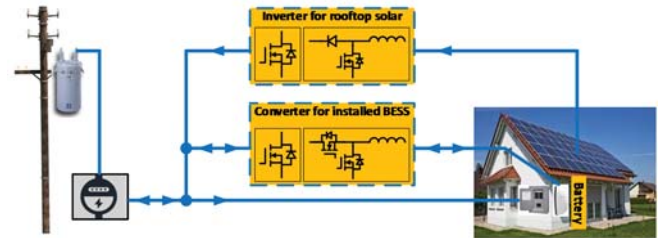


Fig. 1. Conventional rooftop PV and battery energy storage system (BESS) interfaced to the grid via separate dc-ac converters

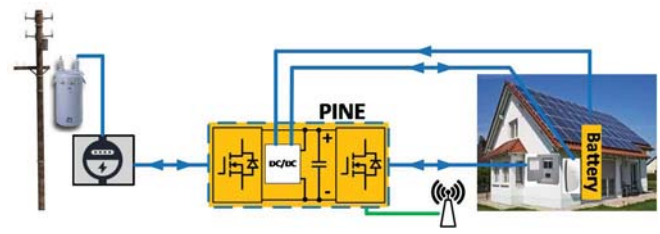


Fig. 2. Proposed power electronics at grid edge - a self-organizing converter with control intelligence at the edge of the electric distribution network.

It is noted that the house/load is directly connected to the grid and the residential load is susceptible to grid voltage variations. Further, since the power supplied from the grid is not processed, it is not possible to limit the amount of power delivered to each consumer in case of disaster. Finally, nonlinear loads in the house inject harmonic currents into the grid distribution system.

In view of this, this paper focuses on self-organizing power electronics intelligence at the very edge of the electric distribution network. The resultant paradigm of grid operation is termed power electronics intelligence at the network edge (PINE) as shown in Fig. 2, first introduced in [7]. The proposed converter is deployed at the very edge of the network, i.e., behind the electric meter, enabling the utility company to perform energy budgeting during disaster events, while keeping the end-users' voltage constant, and maintaining unity power factor at the grid interface level during normal operation, as shown in Fig 2. PINE can also be controlled to inject reactive power to the grid for volt var control (VVC). Fig. 3a-b shows the proposed PINE topology in more detail.

The main advantages of the proposed power electronics at the grid edge concept (Fig. 2) are:

- Energy budgeting i.e. the output power supplied to the home (load) can be limited based on power availability (ex: during disasters). This limit can be enabled remotely.
- Output voltage (home/load) is regulated via PWM control of the output converter.

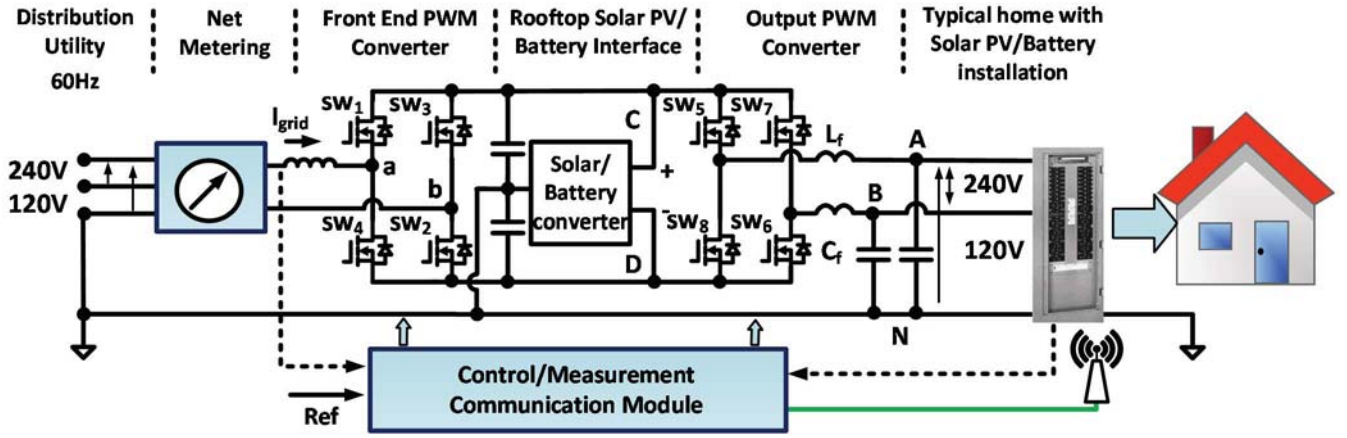


Fig. 3a. Proposed topology of the Power Electronic Intelligence at the Network Edge (PINE) concept. Both roof-top solar PV and BESS are integrated into the dc-link.

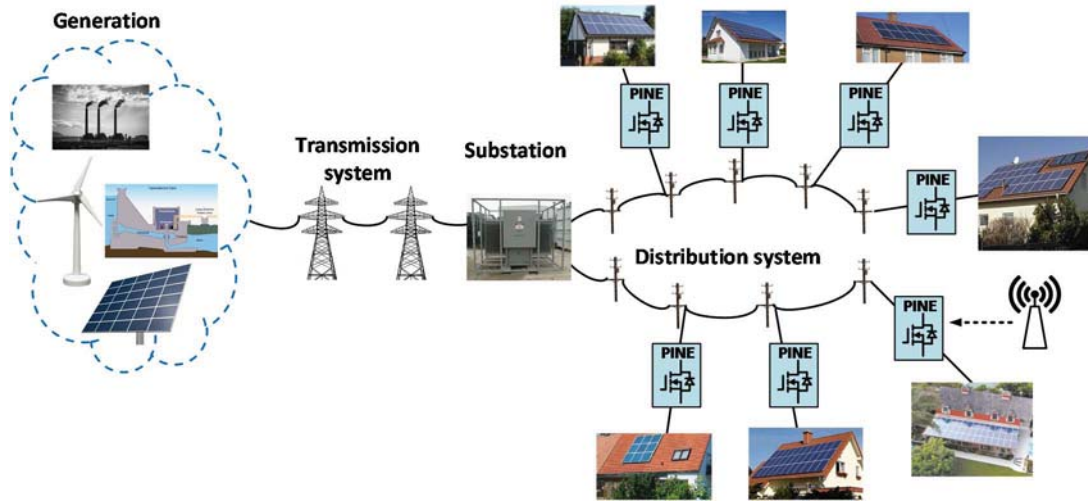


Fig. 3b. Schematic depiction of a self-organizing grid with the proposed PINE concept.

- Input current is controlled to be harmonic free and at unity power factor (PF). This further reduces delivery losses [7].
- Cost of the PINE converter is compatible with a PV inverter and BESS converter. The proposed technology is deployed down at the very edge of the network.
- Input utility voltage can vary over a wider range since the front-end converter can regulate the dc-link voltage. This feature allows for further optimization of distribution losses [7].
- PINE is based on distributed decision-making without any need for coordination.
- Power flow is bidirectional.

This work focuses on energy budgeting control to limit the power delivered to each consumer when the available energy is limited. This is achieved by limiting the current in the output PWM converter.

## II. PROPOSED PINE TOPOLOGY

The proposed PINE concept, as shown in Fig. 3a, is designed to power the 120/240V split phase loads in a typical home and consists of three main stages: a front end converter that draws/injects sinusoidal current from/to the

utility, a rooftop solar PV/Battery system connected to a DC link and an output PWM converter that feeds the load. Since the power from the grid is handled entirely by the proposed topology, energy budgeting is available during disaster events, and during normal operation, the circuit is able to operate over a wide range of input voltage (from 0.8 pu to 1.2 pu), while maintaining harmonic free input current at unity power factor. In addition, this circuit allows bidirectional power flow and control of real and reactive power flow.

### Front end PWM converter (Fig. 3a)

The front end converter (Fig. 3a) draws sinusoidal current from the grid. Less current harmonics significantly reduces line losses, components overheating and transformer ratings in the distribution network. The front end converter can also be controlled as an inverter when the PV is supplying power to the grid.

### Output PWM converter (Fig. 3a)

The output PWM converter generates split phase ac output (120/240V, 60Hz) designed for residential loads. The output L-C filter is designed to maintain a sinusoidal output voltage under a variety of load conditions. During disaster events, the output maximum allowable power for

Fig. 4. Energy budgeting control scheme, enabled by current limit strategy.



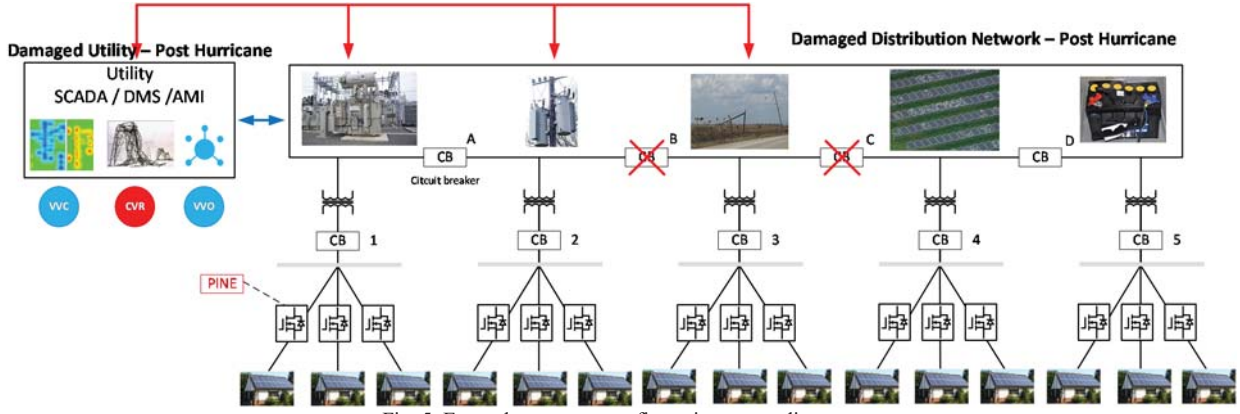


Fig. 5. Example system reconfiguration – post disaster.

Limiting the output current will in turn reduce the output voltage magnitude. According to the CBEMA curve, the minimum allowable threshold for an under voltage for more than 10 seconds is 0.87 p.u.

To avoid reducing the output voltage below the 0.87 p.u. limit, this work takes advantage of the recent developments in management devices with Internet-of-Things (IoT) technology enabled. If the voltage reduces from a given limit, the loads can be turned off remotely, returning to an acceptable voltage magnitude.

#### IV. ENERGY BUDGETING SCENARIOS DESIGN AND SIMULATION RESULTS

In this section, examples of 3 different budgeting scenarios are presented to show how the proposed PINE can control the power flow between the grid and a house. Fig. 5 shows an example of reconfigured system immediately after a disaster such as a hurricane passing. It can be seen that bulk transmission lines are down as well as damage to local solar generation. Circuit breakers (CB) B and C are commanded to isolate the faulted lines. The first two group of homes on the left are shown to have functioning distribution via CB-A, while the third group of homes fed by CB-3 are essentially on their own operating in an islanded mode. Similarly, the two home groups on the right are functioning with CB-D and CB-4, CB-5 operational.

The proposed PINE topology limits the maximum amount of power delivered to each house, to enable energy budgeting mode.

##### Scenario 1

For this scenario, the simulated PINE is located in the group of homes fed by CB-1, since the local solar generation is damaged, the house needs to be fed by the grid, Fig. 6 shows the power fed to a PINE as the available power from the grid keeps reducing due to continuing damage in the utility/distribution infrastructure.

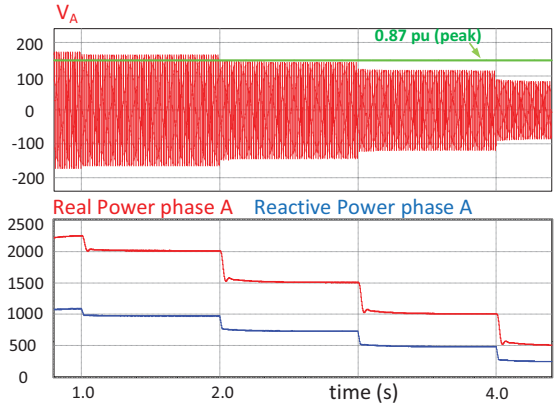


Fig. 6. Energy budgeting scenario 1, after  $t = 2$  seconds, the limit is 1.5 kW, and the voltage reduces below 0.87 p.u.

Table 1 summarizes the maximum allowable power (per phase) as the disaster evolves for the first two scenarios.

Table 1. Power limit assigned for each house, per phase, for scenarios 1 and 2. The power factor is 0.9

Time (s)	$t < 1$	$1 < t < 2$	$2 < t < 3$	$3 < t < 4$	$4 < t$
$P_{max}$	No limit	2.0 kW	1.5 kW	1.0 kW	0.5 kW

In this scenario, there is no control over the load, to show how the voltage could reduce below allowable limits. The load has a 90% power factor (inductive), since the real power is being limited, the reactive power keeps adjusting and the power factor remains at 90%. It can be seen that after 2 seconds, when the limit is 1.5 kW, the output voltage reduces below the limits indicated in the CBEMA curve.

##### Scenario 2

In the second scenario, the same situation is simulated, adding the ability to connect/disconnect the loads remotely. Fig. 7 shows how when the output voltage reduces from a given limit, the non-essential loads can be disconnected as needed, keeping the voltage magnitude above 0.87 p.u. Each time the voltage goes below 0.87 p.u., a non-essential load is disconnected after one cycle.

Table 2 summarizes the times and values for the non-essential loads that are disconnected to maintain the voltage magnitude under desired limits. The essential loads are the only ones not disconnected after 4.32 seconds.

Table 2. Non-essential loads disconnection times and demand.

Load	Disconnection time (s)	Real Power (W)	Reactive Power (VAR)
1	2.02	450	217
2	3.02	450	217
3	3.26	225	108.5
4	4.02	225	108.5
5	4.04	225	108.5
6	4.32	225	108.5
Essential Loads	No disconnection	450	217

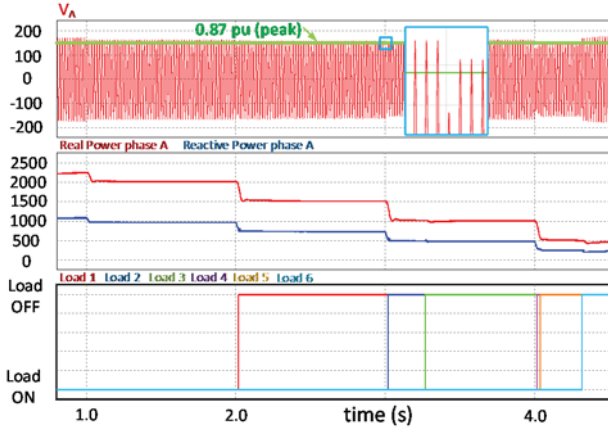


Fig. 7. Energy budgeting scenario 2, when the control results in a voltage below 0.87 p.u., a non-essential load is disconnected, maintaining the voltage in the allowable range.

It can be seen that at 4.02 seconds, load 4 is disconnected, but since the voltage magnitude does not increase to an acceptable level, load 5 is then disconnected after an additional cycle to increase the output voltage above 0.87 p.u. This ensures that the essential needs are met during a disaster scenario with an appropriate output voltage magnitude.

### Scenario 3

For the third scenario, the simulated PINE is located in the group of homes fed by CB-3, since there is available power from the PV/Battery system to spare, the extra amount is used to provide the microgrid, but as their need decreases, the rest of the power can be supplied as reactive power for volt-var control purposes. The results are shown in Fig. 8.

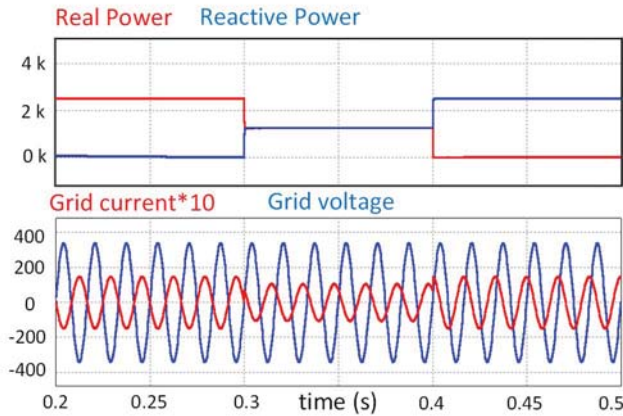


Fig. 8. Scenario 3, the PINE converter provides real and/or reactive power to the microgrid.

In the final simulation, the PINE converter operation is shown under normal operating conditions (no disaster) to show how it can handle voltage variations in the grid while maintaining the load voltage constant, as shown in Fig. 9. This allows the bus voltages in the distribution system to fluctuate a larger range.

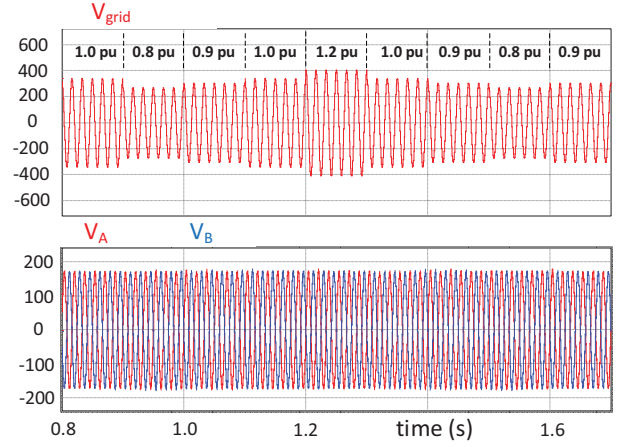


Fig. 9. PINE converter operation during normal operating conditions, when voltage variations occur, the proposed PINE concept maintains the load voltage constant.

## V. HARDWARE RESULTS

A laboratory prototype of PINE is currently under development. Figs. 10 and 11 show the experimental results for the proposed output PWM converter voltages and currents.

Fig. 10 shows phase currents  $I_A$ ,  $I_B$ , and output voltages  $V_A$  and  $V_B$ , of the output PWM converter, as can be seen, when the energy budget strategy is implemented, the output voltage magnitude reduces from 60 V to 42 V, reducing the output power from 300 W to 147 W per phase.

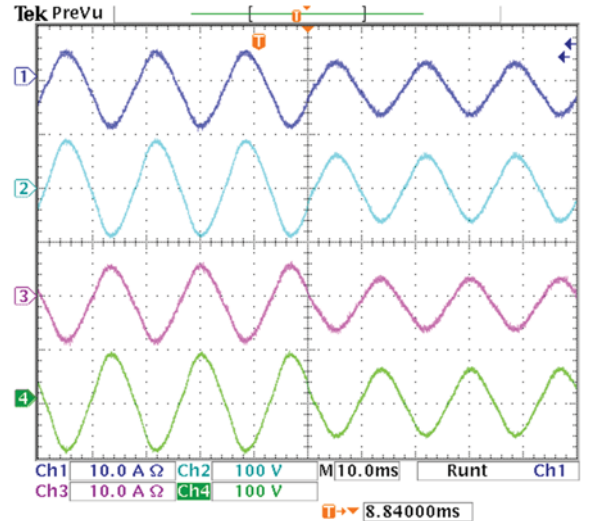


Fig. 10. Experimental waveforms of laboratory prototype output PWM converter voltages and currents. Channel 1 shows phase current  $I_A$ , Channel 2 shows phase voltage  $V_A$ , Channel 3 shows phase current  $I_B$  and Channel 4 shows phase voltage  $V_B$ .

Fig. 11 shows phase current  $I_A$  and phase voltage  $V_A$ , before and after filter, under the energy budgeting state, the switching frequency of the converter is 20 kHz.

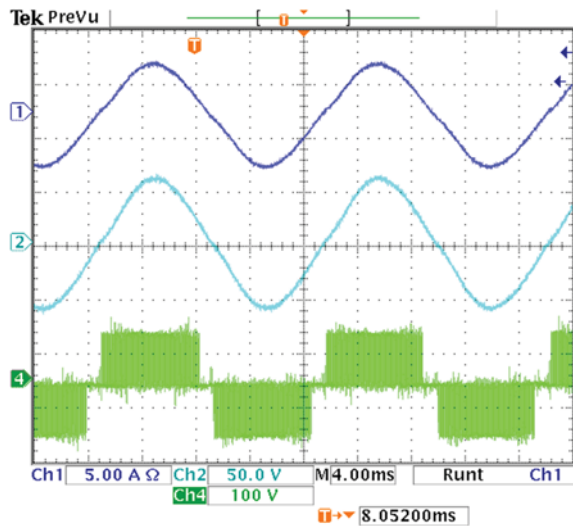


Fig. 11. Experimental waveforms of laboratory prototype output PWM converter current  $I_A$ , and voltage  $V_A$ , before and after filter. Channel 1 shows phase current  $I_A$ , Channel 2 shows phase voltage  $V_A$ , and Channel 4 shows the unfiltered voltage  $V_A$ , the switching frequency is 20 kHz.

## VI. CONCLUSIONS AND FUTURE WORK

In this paper, a self-organizing power electronic converter with control intelligence at the edge of the electric distribution network has been proposed. The proposed PINE concept has been shown to have the potential to make the future electricity delivery system more internet-like (i.e. intelligence at the network edge). A current limiting control strategy has been implemented to limit the output power delivered to the load. This feature has been shown to be particularly useful during natural disasters. During normal conditions the PINE approach has been shown to maintain output voltage regulated. Simulation and hardware results have been shown to validate the proposed concept.

## REFERENCES

- [1] V. S. S. Kumar, L. Xie, and P. R. Kumar, "An Analytical Approach for Loss Minimization and Voltage Profile Improvement in Distribution Systems with Renewable Energy Resources," *IREP Symposium 2017*.
- [2] H. G. Yeh, D. F. Gayme, and S. H. Low, "Adaptive VAR Control for Distribution Circuits With Photovoltaic Generators," *IEEE Trans on Power Systems*, vol. 27:3, pp. 1656–1663, Aug. 2012.
- [3] A. Kwasinski, V. Krishnamurthy, J. Song and R. Sharma, "Availability Evaluation of Micro-Grids for Resistant Power Supply During Natural Disasters," in *IEEE Transactions on Smart Grid*, vol. 3, no. 4, pp. 2007-2018, Dec. 2012.
- [4] C. Abbey et al., "Powering Through the Storm: Microgrids Operation for More Efficient Disaster Recovery," in *IEEE Power and Energy Magazine*, vol. 12, no. 3, pp. 67-76, May-June 2014.
- [5] L. Comfort, A. Boin, C. Demchak et al, editors, *Designing Resilience: Preparing for Extreme Events*, Univ. of Pittsburgh Press, 2010.
- [6] V. Vega-Garita, L. Ramirez-Elizondo, G. R. C. Mouli and P. Bauer, "Review of residential PV-storage architectures," *2016 IEEE International Energy Conference (ENERGYCON)*, Leuven, 2016, pp. 1-6.
- [7] H. M. Chou, L. Xie, P. Enjeti and P. R. Kumar, "Power electronics intelligence at the network edge (PINE)," *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, Cincinnati, OH, 2017, pp. 5214-5221.

- [8] J. T. Hawke, H. S. Krishnamoorthy and P. N. Enjeti, "A Family of New Multiport Power- Sharing Converter Topologies for Large Grid-Connected Fuel Cells," *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 2:4, pp. 962-971, Dec. 2014.
- [9] B. Zhao, Q. Song, W. Liu and Y. Sun, "Overview of Dual-Active-Bridge Isolated Bidirectional DC–DC Converter for High-Frequency-Link Power-Conversion System," in *IEEE Transactions on Power Electronics*, vol. 29, no. 8, pp. 4091-4106, Aug. 2014.
- [10] EATON, "Energy management circuit breaker". Available: <http://www.eaton.com/FTC/utilities/EMCB/index.htm>. [Accessed: May-18-2018].
- [11] R. Zhang, M. Cardinal, P. Szczesny and M. Dame, "A grid simulator with control of single-phase power converters in D-Q rotating frame," *2002 IEEE 33rd Annual IEEE Power Electronics Specialists Conference. Proceedings (Cat. No.02CH37289)*, Cairns, Qld., Australia, 2002, pp. 1431-1436 vol.3.
- [12] M. Gonzalez, V. Cardenas and F. Pazos, "DQ transformation development for single-phase systems to compensate harmonic distortion and reactive power," *9th IEEE International Power Electronics Congress, 2004. CIEP 2004*, Celaya, Gto., Mexico, 2004, pp. 177-182.